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SDSS J142625.71+575218.3: THE FIRST PULSATING WHITE DWARF WITH A LARGE DETECTABLE MAGNETIC FIELD

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ABSTRACT

We report the discovery of a strong magnetic field in the unique pulsating carbon-atmosphere white dwarf SDSS J142625.71+575218.3. From spectra gathered at the MMT and Keck telescopes, we infer a surface field of $B_s \simeq 1.2$ MG, based on obvious Zeeman components seen in several carbon lines. We also detect the presence of a Zeeman-splitted He I 4471 line, which is an indicator of the presence of a non-negligible amount of helium in the atmosphere of this Hot DQ star. This is important for understanding its pulsations, as nonadabatic theory reveals that some helium must be present in the envelope mixture for pulsation modes to be excited in the range of effective temperature where the target star is found. Out of nearly 200 pulsating white dwarfs known today, this is the first example of a star with a large detectable magnetic field. We suggest that SDSS J142625.71+575218.3 is the white dwarf equivalent of a roAp star.

Subject headings: stars: abundances – stars: atmospheres – stars: individual (SDSS J1426+5752) – stars: magnetic fields – white dwarfs – roAp

1. INTRODUCTION

Recently, Dufour et al. (2007) reported the discovery of a new type of white dwarf stars with an atmosphere composed primarily of carbon with little or no traces of hydrogen or helium (the "Hot DQ" spectral type). Prior to that discovery, white dwarfs cooler than $\sim$ 80,000 K were known to come in essentially two flavors: those with an almost pure hydrogen surface composition (forming the DA spectral type), and those with a helium-dominated surface composition (the non-DA stars, which comprise the DO, DB, DC, DZ, and DQ spectral types). Pulsationally unstable stars are found among these two broad families of white dwarfs, in each case occupying a narrow range of effective temperature. Variable white dwarfs situated in these instability strips are, respectively, classified ZZ Ceti stars (hydrogen atmospheres, $T_{\rm eff} \sim 12{,}000$ K) and V777 Her stars (helium atmospheres, $T_{\rm eff} \sim 25{,}000$ K). Since each of these instability regions is associated with the presence of a partial ionization zone of the primary atmospheric constituent (H or He), it was naturally expected that some carbon-atmosphere white dwarfs could be unstable as well in a certain regime of effective temperature corresponding to partial ionization of carbon. And indeed, Fontaine & Van Horn (1976) found long ago strong similarities between the partial ionization regions and associated superficial convection zones of white dwarf models with H-, He-, and C-dominated atmospheres/envelopes. Theoretical considerations thus suggested that some of the Hot DQ white dwarfs, because they are located in a narrow range of effective temperature around 20,000 K (Dufour et al. 2007, 2008), could possibly pulsate. Following this, a systematic search for pulsations in carbon-atmosphere white dwarfs carried out by Montgomery et al. (2008) successfully discovered the first pulsating carbon-dominated atmosphere white dwarf: SDSS J142625.71+575218.3 (hereafter SDSS J1426+5752). They uncovered a single pulsation (and its first harmonic) with a period of 417 s in that star.

In parallel with this observational effort, Fontaine et al. (2008) carried out the first detailed stability study, based on the full nonadiabatic approach, to investigate the asteroseismological potential of carbon-atmosphere white dwarfs. They showed that pulsational instabilities in the range of effective temperature where the Hot DQs are found are indeed possible, but only if a fair amount of helium is present in the atmosphere/envelope compositional mixture. White dwarf models with pure carbon envelopes are found to pulsate, but only at much higher temperatures than those characterizing Hot DQ's discovered up to now. However, the SDSS spectra analyzed in Dufour et al. (2008), even though quite noisy, rule out large amounts of helium (from the absence of the He I λ4471 line) for all objects except SDSS J1426+5752 which, because of its higher surface gravity and lower effective temperature, could perhaps have an He/C abundance ratio as high as 0.5. So, according to the full nonadiabatic models, SDSS J1426+5752 should be the only object pulsating, as observed, provided helium is present in a relatively large amount at the surface. However, even with such an abundance (He/C = 0.5), only a tiny depression at the He I λ4471 line is predicted by synthetic models. Given the noisy SDSS spectrum for this object, no firm conclusion could be reached concerning the presence of helium, although the above mentioned abundance looked quite compatible with the spectroscopic observation (see the SDSS spectrum and fits in Figure 1).

All this motivated us to obtain higher sensitivity ob-

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servations for this special object in order (1) to confirm, as may be the case, the presence of a relatively large amount of helium (thus increasing our confidence in the nonadiabatic approach), and (2) to be able to eventually carry out a full asteroseismological analysis using better constraints/determinations of the atmospheric parameters ($T_{\rm eff}$, $\log g$ and He/C) from spectroscopy. In this Letter, we thus report new high signal-to-noise ratio spectroscopic observations (MMT and Keck) that revealed, to our great surprise, that SDSS J1426+5752 is the first pulsating white dwarf showing clear evidence for the presence of a strong magnetic field. This is certainly an unexpected result, given that strong magnetism in white dwarfs is generally thought to extinguish, or at least greatly diminish, pulsational activity. We discuss below the implications of this discovery.

2. OBSERVATIONS

Since the signal-to-noise ratio for the SDSS spectra of the faint known carbon-atmosphere white dwarfs is not sufficient for a precise determination of the atmospheric parameters, a program to reobserve all the Hot DQ stars with the MMT 6.5 m telescope was recently undertaken. The complete analysis of these new Hot DQ spectra will be presented in due time, once the program is completed. As a part of the program, SDSS J1426+5752 was observed for a total of 180 minutes with the Blue Channel spectrograph on the night of 2008 May 5. We used the 500 line mm^{-1} grating with a 1" slit, resulting in a ~ 3.6 Å FWHM spectral resolution over a wavelength range of 3400-6300 Å. The spectra were reduced with standard IRAF packages. The final combined spectrum, shown in Figure 1, has a signal-to-noise ratio of $\sim$75 at 4500 Å.

A lower signal-to-noise observation was obtained at the Keck Observatory on the night of UT 2008 May 4 with the blue channel of LRIS. The 400 groove mm^{-1}, 3400Å grism was used with the D560 dichoric and the atmospheric dispersion corrector was active. Two exposures with a total exposure time of 1260 seconds were taken with a 0.″7 slit in 0.″9 seeing at an airmass of 2.3. The spectra were reduced and extracted using standard IRAF packages. The spectra were corrected for atmospheric extinction using the IRAF KPNO extinction curve; the measured signal-to-noise is ≈ 54 per 5Å resolution element at 4500Å.

In Figure 1, we present our new high signal-to-noise ratio MMT spectrum, the Keck observation, as well as the SDSS data that were used for the Dufour et al. (2008) analysis. The most striking revelation brought by these new observations is that many of the carbon features are clearly well separated into three Zeeman components (see bottom panels in Figure 1). The separation between the components of the C II features corresponds to a surface field $B_s \approx 1.2$ MG. Note that with the poor signal-to-noise ratio of the SDSS observation, Dufour et al. (2008) could not resolve the Zeeman structure and, as a result, their spectroscopic solution (see Fig. 1) can now only be considered as an approximation of the true atmospheric parameters. Our new observations also reveal a small but quite significant depression near the 4471 He I line, indicating that helium is indeed present in relatively large abundance in this object. However, since our atmosphere models do not include a magnetic field yet, no exact abundance can be derived at this point, although it is probably not too far from the 0.5 value mentioned above.

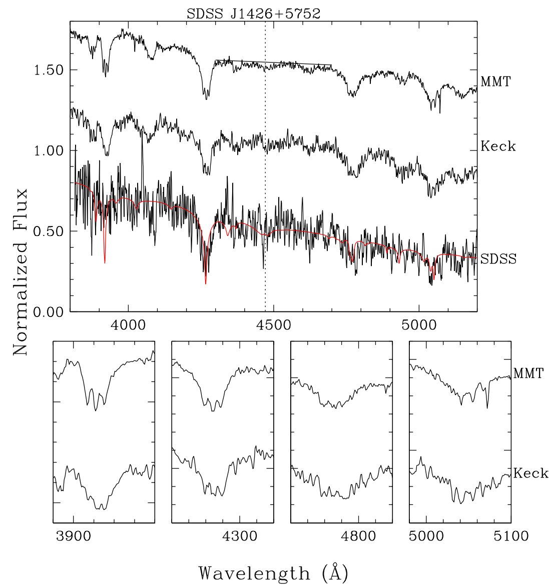

FIG. 1.— *Top:* Spectroscopic observations from SDSS, Keck and MMT, normalized to unity at 4500 Å and offset from each other for clarity. In red is the solution of Dufour et al. (2008) based on the nonmagnetic fit of the noisy SDSS spectrum ($\log g$ = 9.0, $T_{\rm eff}$ = 19,830 K and He/C = 0.5). The dotted line marks the position of the He I λ4471 line. We also added, to show the presence of the small helium absorption, a line representing approximatively the continuum for the MMT spectrum (the other depression near 4625 Å is a carbon feature usually observed in higher $T_{\rm eff}$ objects, indicating that the solution of Dufour et al. (2008) is perhaps slightly underestimated). Note that the SDSS and Keck spectra have been smoothed with a 3 pts average window for clarity *Bottom:* Selected carbon lines from the Keck and MMT spectra that demonstrate the presence of a 1.2 MG magnetic field through Zeeman splitting.

3. DISCUSSION

3.1. *Origin of the Magnetic Field*

It is generally believed that many magnetic white dwarfs are the likely descendants of magnetic main sequence stars (the Ap and Bp stars), and that the high fields observed in some white dwarfs are the result of (partial) magnetic flux conservation of a fossil field as the star shrinks in radius by a factor of ~ 100 as it becomes a white dwarf. Since, however, about ten per cent of isolated white dwarfs are high field magnetic white dwarfs (recognizable from Zeeman split spectral lines, Liebert et al. 2003; Kawka et al. 2007), another origin may also be necessary, possibly as proposed by Tout et al. (2008).

Dynamo-type mechanisms have also been proposed to explain the putative weak magnetic field in the pulsating DB white dwarf GD 358 (Markiel et al. 1994; Thomas et al. 1995). However, it is quite unlikely that such mechanisms could account for a field as high as 1.2 MG in the carbon-rich atmosphere of SDSS J1426+5752, or in a white dwarf in general. Indeed, to produce a dynamo-type magnetic field, convective motions must be strong enough to twist and move seed magnetic lines. As the field grows, due to dynamo amplification, convection is having a harder time to move the field lines. Thus, the final large-scale field can never reach an amplitude

comparable to the so-called equipartition field strength given by the condition $B_{eq}^2/8\pi = 1/2 \ < \rho\, v_{conv}^2 >$, where the last term corresponds to a suitable average over the convection zone of the convective energy density.

Typical values of B_{eq}, calculated for H-, He- and even C-atmosphere white dwarfs by Fontaine et al. (1973) are $\sim$ 10-100 kG. While these results need to be revisited, in particular using a state-of-the art model for SDSS J1426+5752, it would be extremely surprising to find that the order of magnitude estimates of Fontaine et al. (1973) could change significantly. We thus believe that the 1.2 MG magnetic field found in SDSS J1426+5752 is a fossil field, probably originating from an Ap star.

3.2. *Magnetism and Pulsations in White Dwarf Stars*

To date, there is no clear evidence for the presence of an observable magnetic field in any of the known pulsating white dwarfs. None of the 51 bright ZZ Ceti stars from the Bergeron sample show any sign of Zeeman splitting in the optical spectra, which translates, given the typical S/N ratio and resolution of the observations, to limits on the magnetic field strength of about 500 kG (P. Bergeron, private communication). Also, none of the known pulsating DB white dwarfs have a magnetic field strong enough to be detected from Zeeman splitting. This is also the case for the 18 known pulsating white dwarfs of the GW Vir type.

In order to detect weaker magnetic fields down to a few kG, spectropolarimetric measurements are needed. Unfortunately, only a small number of pulsating white dwarfs have been investigated with this more precise method. Nevertheless, no significant magnetic field has ever been found in any of the few pulsating white dwarfs for which spectropolarimetric measurements are available (Schmidt & Grauer 1997; Valyavin et al. 2006), and very small upper limits of a few kG are obtained in all cases (with perhaps an uncertain marginal detection in one case).

The fact that the samples of magnetic and pulsating white dwarfs do not intersect may not be very surprising from a theoretical point of view. Indeed, pulsating white dwarfs of both the V777 Her and ZZ Ceti types are found in a regime of effective temperature where an important superficial convection zone is present. The latter is due to the partial ionization of either He or H, and contributes significantly to the excitation of pulsation modes. For a large scale magnetic field of magnitude much stronger than the equipartition field strength, it is likely that the convective motions are largely quenched, which perhaps extinguishes completely pulsational driving. One example of a white dwarf where a magnetic field ($B_e = -1000 \pm 500$ kG, Putney 1997) might have "killed" the pulsations is the constant DB star LB 8827 (PG 0853+164, Wesemael et al. 2001). Unfortunately, the effective temperature of this object is uncertain, and it is not known with certainty whether it is inside the DB instability strip or not.

The only case where the detection of a magnetic field has been claimed in a pulsating white dwarf is that of GD 358. In that case, the magnetic field has been indirectly inferred from asteroseismological analysis (Winget et al. 1994). It should be noted that this interpretation of the asteroseismological data in terms of a magnetic field is far from being accepted by all (see, e.g., Fontaine & Brassard 2008, in preparation). In any case, follow-up circular polarization measurements of GD 358 by Schmidt & Grauer (1997) have not succeeded in detecting the presence of a weak field, but their detection threshold was significantly above the value of 1300 $\pm$ 300 gauss suggested by Winget et al. (1994). Such a small field is certainly not strong enough to affect the convection zone significantly, and is apparently unable to stop the pulsations in this variable white dwarf.

3.3. *Rotation or Pulsations?*

In this section, we briefly discuss the possibility that rotation might be a significant ingredient in this puzzle. Indeed, rapid rotation is known to be important in at least two variable magnetic white dwarf systems where the variability is explained by changes with rotational phase instead of pulsational instabilities. The first of these cases, RE J0317-853 (Barstow et al. 1995; Burleigh et al. 1999), is a highly magnetic, rotating white dwarf with a period of 725 s that is most probably the result of a double degenerate merger. The second case, Feige 7 (Liebert et al. 1977), is also a rotating magnetic white dwarf but, this time, with a period of 2.2 hours. Its spectrum shows Zeeman splitting for both hydrogen and helium that appears to vary with rotational phase (Achilleos et al. 1992).

Could it be that SDSS J1426+5752 is a rare magnetic white dwarf spinning very fast (which would make it, with a period of 417 s, the fastest white dwarf amongst isolated white dwarfs)? Several factors lead us to believe that, on the contrary, this star is most likely a pulsator and not a rotator. The exposure time for each of our integrations at the MMT (600 s) is well above the period of 417 s found by Montgomery et al. (2008), meaning that our spectra are averaged over a variability cycle. If the luminosity variations are due to fast rotation of the star, it is quite probable that the average magnetic field along our line of sight, depending on the geometry and the alignment of the field with respect to the rotation axis or the presence of magnetic spots, would vary over one cycle. The resulting Zeeman splitting of atomic line should thus vary in magnitude as the field strength changes, leading to very broad or blended lines in our average spectra, not three well separated and sharp components as observed (see bottom panels in Figure 1).

Of course, one could imagine a situation where a dipole field is well aligned with the rotation axis, or a more complex field geometry that is such that the field remains almost constant over the rotation period although our knowledge of other magnetic white dwarfs suggests that this is quite rare and unlikely (Wickramasinghe & Ferrario 2000). This, alone, is not an argument strong enough to discard completely this possibility of fast rotation.

However, our own rapid photometry campaign at the 61" telescope at Mount Bigelow with the Mont4K CCD imager brings an important new piece to this puzzle (Fontaine et al. 2008, in preparation). Indeed, based on a total of 107 hours of observations spread over one month (half in early April and half in early May 2008), the presence of a low-amplitude second mode with a period of 319 s (a 4.9 sigma result) has now been revealed. That SDSS J1426+5752 is therefore very likely a multi-

periodic pulsator is certainly a strong argument against the fast rotator hypothesis. A more standard pulsation mechanism, although involving a strong magnetic field, is thus probably at work here (see below).

Finally, if we look individually at each combination of two consecutive 600 s MMT exposures (a single exposure is too noisy to reveal the splitting in the lines), we do not find any evidence for a change in the separation of the Zeeman components over a three hour period, indicating that the magnetic field strength remains constant over that timescale. Using the Keck data from the previous night, we find that, within the limits of the noise, the spectrum looks unchanged on a $\sim$20 h period as well. Unless we are dealing with a complicated magnetic field geometry or that a dipole field is perfectly aligned with the rotation axis, this probably indicates that this star is rotating very slowly, which is more in line with our understanding that magnetic white dwarfs are generally slow rotators (Wickramasinghe & Ferrario 2000).

3.4. *A roAp Star Analog?*

As discussed above, the magnetic field in SDSS J1426+5752 is certainly much stronger than B_{eq}, which immediately suggests that the convective motions are smothered by the field and perhaps even that there is no convection at all. At the very least, because ionized matter cannot freely cross field lines, one would expect the suppression of convective motions in the magnetic equatorial regions while some “channeled” motions could resist near the magnetic poles. Since convection plays a role in the driving of pulsation modes in nonmagnetic models of SDSS J1426+5752, how is it possible then that a white dwarf with such a high magnetic field, and perhaps no significant convection zone, pulsates?

If we take a look across the wide field of stellar oscillations, we find that there is a perfect example of a class of objects where pulsations and magnetism are found to coexist: the rapidly oscillating Ap (roAp) stars (Kurtz 2006). These stars have a strong (by main sequence standards) magnetic field (1000-10,000 G), no convection, and pulsation modes are excited through a kappa-type mechanism. It could thus be that SDSS J1426+5752 is a white dwarf analog of the roAp stars. Amusingly, it is also not impossible that it might have pulsated as a roAp itself in a distant past! The full nonadiabatic calculations presented in Dufour et al. (2008) rely on equilibrium models that all have convection zones, and are thus likely inappropriate for the case of SDSS J1426+5752. One interesting avenue we intend to explore is to construct models in which we would prevent artificially convection in order to mimic the effects of the magnetic field. Would artificially radiative models pulsate? We do not know yet, but it would not be surprising that they could via the usual kappa-mechanism since there would still be, convection or not, a huge opacity peak in the envelope of such models. While the magnetic field is probably sufficiently strong to inhibit convective motions, it is not strong enough to stop the pulsations themselves, very obviously because we detect oscillation modes. The effect of the strong field on the pulsations is probably indirect in that it changes the conditions for driving, but much more work is required before we understand exactly how this occurs. The presence of the field may also force the pulsations to align themselves on the magnetic axis as in roAp stars. The body of knowledge gathered so far on these stars should be extremely useful as a guide for future investigations of the pulsation properties of SDSS J1426+5752.

4. CONCLUSION

We presented evidence that SDSS J1426+5752 is the first pulsating white dwarf with the clear presence of a strong (i.e., strong enough for Zeeman splitting to be observed) magnetic field ($\approx$ 1.2 MG). Such a strong magnetic field probably inhibits the convective motions in this object, but it is unclear yet how the pulsations are affected. We proposed that this strange object could be a white dwarf analog of the rapidly oscillating Ap stars and that a usual kappa-mechanism, even in the absence of convection, might still explain the pulsational instabilities. The confirmed presence of helium in the envelope/atmosphere of SDSS J1426+5752 is likely to play a key role in this process. Future work testing this hypothesis is underway.

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